UNIVERSIDADE FEDERAL DO PARANÁ

BRUNO HENRIQUE DE MOURA MERSS

TOPOGRAFIA SÍSMICA E CARACTERÍSTICAS INTERNAS DE UM COMPLEXO DE TRANSPORTE EM MASSA DE IDADE MAASTRICHTIANA

CURITIBA

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Dissertação apresentada ao curso de Pós-Graduação em Geologia, Setor de Ciências da Terra, Universidade Federal do Paraná, como requisito parcial à obtenção do título de Mestre em Geologia Exploratória.

Orientadora: Profa. Dra. Barbara Trzaskos

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TERMO DE APROVAÇÃO

Os membros da Banca Examinadora, designada pelo Colegiado do Programa de Pós-Graduação em GEOLOGIA da Universidade Federal do Paraná, foram convocados para realizar a arguição da Dissertação de Mestrado de **BRUNO HENRIQUE DE MOURA MERSS**, intitulada: **TOPOGRAFIA SÍSMICA E CARACTERÍSTICAS INTERNAS DE UM COMPLEXO DE TRANSPORTE EM MASSA DE IDADE MAASTRICHTIANA**, sob orientação da Profa. Dra. BÁRBARA TRZASKOS, após terem inquirido o aluno e realizado a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.

A outorga do título de Mestre está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

Curitiba, 19 de março de 2020.

BÁRBARA TRZASKOS
Presidente da Banca Examinadora

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Avaliador Externo (PETROBRAS)

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RESUMO

A caracterização de complexos e/ou depósitos de transporte em massa é usualmente realizada com o objetivo de compreender a cinemática do fluxo e a localização dos três diferentes domínios morfológicos: proximal, translacional e distal. Essa caracterização é realizada tanto em complexos/depósitos recentes quanto em antigos. O objeto de estudo, o complexo de transporte em massa Maricá (MMTC), é um depósito de idade Maastrichtiana que teve sua deposição relacionada com a Progressão Juréia. O objetivo é caracterizar a paleotopografia na qual o MMTC foi depositado, e qual influencia ela teve sobre as características internas do depósito. Essa descrição foi realizada a partir da análise e intepretação de sísmica de alta resolução e atributos sísmicos. Como resultados, foi possível reconstruir a topografia Maastrichtiana e, caracterizar três sismofácies caóticas: amorfa, híbrida e acamadada. As diferentes sismofácies representam variações de velocidade e no grau de homogeneização do fluxo devido a presença de blocos remanescentes (barreiras). Quando o fluxo se movimenta sobre esses blocos, a homogeneização é menor, como resposta à diminuição da velocidade. Essa menor homogeneização pode resultar em melhores reservatórios, ainda mais quando a área fonte é conhecida. Quando o fluxo se movimenta em locais desobstruídos (sem barreiras) ele sofre uma maior homogeneização, resultado de uma maior velocidade. Essa maior homogeneização pode resultar em selos regionais. No caso do MMTC esses dois casos ocorrem, o canal leste é intensamente controlado por barreiras, já o oeste é desobstruído. Essa dualidade mostrou que a caracterização das diferentes sismofácies caóticas pode ser útil na determinação de selos e reservatórios regionais quando procurando *plays* em ambientes com depósitos de transporte em massa.

Palavras-chave: Complexo de transporte em massa; Sismofácies caóticas; Bacia de Santos.

ABSTRACT

The characterization of mass-transport complexes and/or deposits is usually focused on understanding the flow's kinematics and the location of the three different morphological domains: headwall, translational and toe. This characterization is executed in both recent and ancient complexes and/or deposits. The object of study is the Maricá mass-transport complex (MMTC) which is a Maastrichtian complex that is related to the Juréia Progradation. The objective of this research is the characterization of the paleotopography where the MMTC was deposited and comprehend the influence of it in the complex's internal characteristics. This characterization was possible with the analysis and interpretation of high-resolution seismic data and seismic attributes. As results we were able to reconstruct the Maastrichtian topography as well as characterize three different chaotic seismic facies: amorphous, hybrid and layered. Which seismic facies represent variation of velocity and the degree of homogenization that the flow experience in the present of remnant blocks (barriers). When the flow moves over remnant block the velocity decreases and causes a weak sediment homogenization. This weak homogenization could result in better reservoirs, especially if the source area is known. When the flow moves over an unrestricted area the velocity is higher, causing the increase of homogenization. This high homogenization could lead to the generation of regional seals for the oil industry. In the case of study this two cases happen. The eastern channel is heavily controlled by blocks, while the western is flatter. This duality could be useful when determining regional seals and reservoirs of deep-water environments that have mass-transport complexes and/or deposits

Keywords: Mass-transport complex; chaotic seismic facies; Santos Basin

LISTA DE FIGURAS

LISTA DE ABREVIATURAS OU SIGLAS

ANP	- Agência Nacional do Petróleo, Gás Natural e Biocombustíveis
km	- Quilômetros
m	- Metros
MMTC	- *Maricá mass-transport complex* / Complexo de transporte em massa Maricá
ms	- Milissegundo
MTC	- *Mass-transport complex*
MTD	- *Mass-transport deposit*
Myr/My	- Milhões de anos
PSTM	- *Kirchhoff Post-Stack Time Migration*
s	- Segundo

SUMÁRIO

1 INTRODUÇÃO

Movimentos de transporte em massa têm um papel importante na formação de muitas margens continentais (Butler & Turner 2010). Seus produtos podem resultar em reservatórios, selos e horizontes guias para a indústria do petróleo. Seus processos podem afetar seres humanos devido a geração de tsunamis e desestabilização de infraestrutura marinha, como plataformas, portos e cabos de telecomunicação (Fukuda et al. 2015). O uso da sísmica tem sido constante para relevar esses produtos, tanto recentes quanto antigos (e.g. Frey-Martinez et al. 2005; Frey-Martinez et al. 2006; Moscardelli et al. 2006; Scarselli et al. 2016; Lackey et al. 2018; Omeru & Cartwright 2019; Steventon et al. 2019). A maioria desses estudos focaram na caracterização de indicadores cinemáticos e aspectos morfológicos para a compreensão da arquitetura interna e da localização dos três diferentes domínios morfológicos (*sensu* Bull et al. 2009).

Visto que autores tendem a simplificar a caracterização de sismo-fácies caóticas em linhas sísmicas (e.g. Frey-Martinez et al. 2005; Gafeira et al. 2010; Berton & Vesely 2016; Omeru & Cartwright 2019), esse trabalho vem como um esforço para melhorar essa caracterização. Esse aprimoramento é dado pela separação de tipos de sismo-fácies caóticas e sua localização ao longo do complexo. Somado a isso, o presente trabalho também investigou qual foi o papel da topografia no posicionamento dessas diferentes sismo-fácies durante a deposição do fluxo.

1.1 ESTRUTURA DA DISSERTAÇÃO

O trabalho está estruturado em três capítulos. O primeiro visa introduzir o tema da dissertação, mostrando os objetivos, área de estudo e contexto geológico, materiais e métodos utilizados na pesquisa. O segundo, apresenta o artigo completo intitulado “Underlying topography and internal chaotic characteristics of a Maastrichtian Mass-transport Complex”, que será submetido junto a revista Marine and Petroleum Geology. O terceiro capítulo, traz as considerações finais da pesquisa e, por fim, as referências bibliográficas utilizadas na dissertação.

1.2 OBJETIVOS

O objetivo principal da pesquisa é compreender a distribuição espacial de sismo-fácies caóticas e o papel da topografia durante a deposição do Complexo de Transporte em Massa Maricá. Para alcançar esse objetivo foi necessária a conexão dos seguintes objetivos secundários:

- Interpretação e mapeamento, em seções 2D, das diferentes sismo-fácies caóticas presentes;
- Interpretação e mapeamento, em superfícies 3D, das diferentes sismo-fácies caóticas presentes;
- Geração de um cubo sísmico horizontalizado pela superfície correspondente ao Maastrichtiano;
- Criação de mapa topográfico tendo o Maastrichtiano como *datum*.

1.3 CONTEXTO GEOLÓGICO E ÁREA DE ESTUDO

A Bacia de Santos tem aproximadamente 350.000 km² e está localizada na margem continental do sudeste brasileiro, é delimitada a norte pelo Alto de Cabo Frio e a sul pelo Alto de Florianópolis (Figura 1D; Mohriak 2012). A área de estudo está inserida no *survey* BS-500, que tem aproximadamente 9000 km² (Figura 1D).

A bacia representa aproximadamente 140 My. de evolução, desde a quebra do Gondwana, a abertura do Oceano Atlântico e os dias atuais (Moulin et al. 2010). Essa evolução é reconhecida nas três supersequências que definem a história cronoestratigráfica da bacia. Segundo Moreira et al. (2007) a bacia é dividida nas supersequências rifte, pós-rifte e drifte. A primeira (Barremiano ao Aptiano) é o produto inicial da abertura do Atlântico, e é representada por basaltos da Formação Camboriú, arenitos heterolíticos, conglomerados e siltitos da Formação Piçarras, e por fim, carbonatos e folhelhos da Formação Itapema. A supersequência pós-rifte (Aptiana) é caracterizada pelas formações Barra Velha e Ariri, a primeira é representada por microbialitos, e a segunda por evaporitos. Por fim, a supersequência drifte, que envolve processos halocinéticos e tectônicos associados à sua evolução (Caldas & Zalán 2009). É representada pelos grupos Camburi, Frade e Itamambuca, e são compostos basicamente por rochas formadas em ambiente francamente marinho. Em relação ao intervalo foco do estudo, o Maastrichtiano engloba as Formações Santos, Juréia e Itajaí-Açu e o Membro Ilhabela. O Maastrichtiano corresponde a sequência K130 de Moreira et al. (2007) (Figura 2D) e é composta por arenitos resultantes de fluxos turbidíticos densos, folhelhos e siltitos, arenitos plataformais a costeiros e conglomerados continentais.

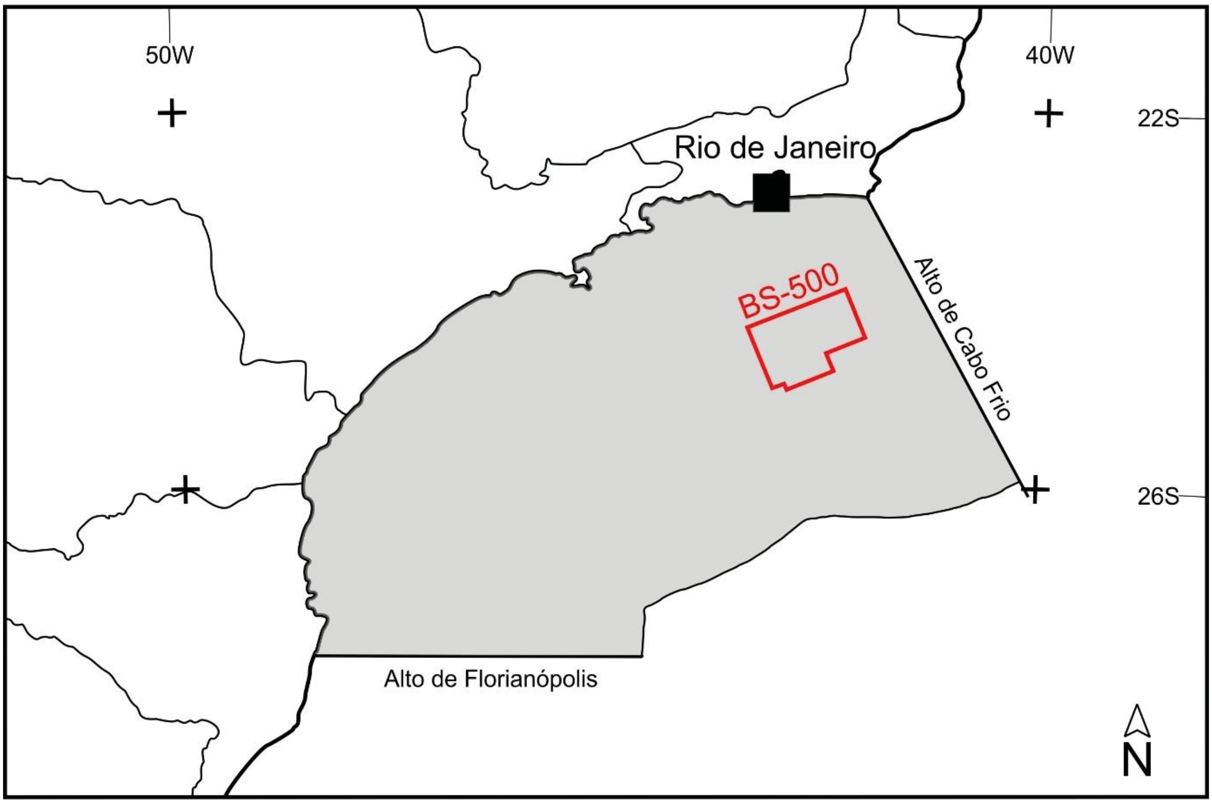


Figura 1D. Localização da área de trabalho e a Bacia de Santos.

O Complexo Maricá é o produto de um processo de escorregamento e tem um volume aproximado de 150 km^3, que ocupa uma área de aproximadamente 1000 km² (Carlotto & Rodrigues 2009). Geograficamente, o objeto de estudo está localizado a aproximadamente 150km do município do Rio de Janeiro (Figura 1D), e estratigraficamente está localizado na porção basal da sequência K130 (Supplementary Material A) (Carlotto & Rodrigues 2007).

1.4 MATERIAS

Durante o desenvolvimento da pesquisa foram analisados dois tipos de dados públicos. Esses dados foram obtidos através de um pedido junto à Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP). O primeiro é um *survey* sísmico 3D do tipo Kirchhoff Post-Stack Time Migration (PSTM) com cerca de 9000 km^2 intitulado BS-500 (Figura 1D), que foi cortado na área de trabalho, resultando num *survey* com 1000 km^2. O segundo é um conjunto de dados do poço: 6-BRSA-556.

1.5 MÉTODOS

A junção dos dois tipos de dados foi feita através do *software* OpendTect PRO 6.4.2., assim como todos os processamentos e cálculos de atributos sísmicos. A junção do poço com a sísmica foi realizada através da criação de um modelo *synthetic-to-seismic*, que posteriormente foi otimizado pelos valores de *check-shot* disponíveis no perfil composto do poço 6-BRSA-566.

Após a junção do poço e da sísmica foram mapeados os horizontes superior e inferior do Complexo Maricá. Ambos foram mapeados num *step inline-crossline* de 2 por 2 e posteriormente foram triangulados a partir do algoritmo *nearest neighbor interpolation distance*, presente no *software* Surfer 13 da empresa Golden Software. Finalmente, os horizontes foram filtrados pela média visando criar superfícies mais suaves e com menor presença de artefatos.

Os atributos sísmicos utilizados foram calculados a partir do *dip-steering Principal Component Analysis* (PCA), que serve como guia sísmico e melhora a qualidade dos atributos baseados neste (De Groot et al. 2004). O primeiro atributo calculado foi o *Dip-Steered Similarity* que expressa a “similaridade” entre dois ou mais pontos adjacentes (Bahorich & Farmer 1995; De Groot & Bril 2005). Esse serve para realçar mudanças de fácies sísmicas e descontinuidades estruturais, para a presente pesquisa o atributo foi usado para visualizar a presença de grandes blocos relictos e blocos em jangada. Por fim, o atributo *Shaded Relief* foi calculado para realçar descontinuidades, e foi baseado no fluxograma proposto por De Groot & Bril (2005) e Farrukh (2009).

A horizontalização da superfície superior do complexo foi realizada no *software* OpendTect PRO 6.4.2. e foi executada para criar um *datum* cronoestratigráfico que representa o Maastrichtiano, período no qual o Maricá foi depositado (Carlotto & Rodrigues 2009). Essa horizontalização foi realizada visando recriar a paleotopografia na qual o Maricá foi depositado. Visto que a área de estudo apresenta intensa deformação causada por sal (Caldas & Zalán 2009), a horizontalização deve ter causado distorções e artefatos (Bland et al. 2004), apesar disso, a interpretação levou em consideração o produto direto da horizontalização.

Acessando o interior no Complexo Maricá, através da adição de 50ms no horizonte superior, foi possível descrever as características quando visualizando em plano. Para isso foram utilizados os atributos *dip-steered similarity* e decomposição espectral. Por fim, visualizando seções do Complexo Maricá, foram caracterizadas diferentes sismofácies que foram separadas devido a diferenças em comprimento, continuidade lateral e vertical e geometria.

2 RESULTADO

1.1 UNDERLYING TOPOGRAPHY AND INTERNAL CHAOTIC CHARACTERISTICS OF A MAASTRICHTIAN MASS-TRANSPORT COMPLEX

Abstract

The characterization of mass-transport complexes and/or deposits is usually focused on understanding the flow's kinematics and the location of the three different morphological domains: headwall, translational and toe. This characterization is executed in both recent and ancient complexes and/or deposits. The object of study is the Maricá mass-transport complex (MMTC) which is a Maastrichtian deposit that is related to the Juréia Progradation, at Santos Basin, Brazil. The objective of this paper is the characterization of the paleotopography where the MMTC was deposited and comprehend the influence of it in the complex's internal characteristics. This characterization was possible with the analysis and interpretation of high-resolution seismic data and seismic attributes. As results we were able to reconstruct the Maastrichtian topography as well as characterize three different chaotic seismic facies: amorphous, hybrid and layered. Such seismic facies represent variation of velocity and the degree of homogenization that the flow undergo in the present or absence of remnant blocks (barriers). When the flow moves over remnant block the velocity decreases and causes a weak sediment homogenization. This weak homogenization could result in better reservoirs, especially if the source area is known. When the flow moves over an unrestricted area the velocity is higher, causing the increase of homogenization. This high homogenization could lead to the generation of regional seals for the petroleum systems. In the studied case this two situations happen. The eastern channel is heavily controlled by blocks, while the western is flatter. This duality could be useful when determining regional seals and

reservoirs of deep-water environments that have mass-transport complexes and/or deposits

Keywords: Mass-transport complex; chaotic seismic facies; Santos Basin

1 Introduction

Seismic data have been extensively used to reveal and understand both recent and ancient underwater mass-transport complexes (MTC) and deposits (MTD) (e.g. Scarselli et al. 2016; Lackey et al. 2018; Omeru and Cartwright 2019; Steventon et al. 2019). Most of the studies have focused on characterizing kinematics indicators as well their location within the MTD/MTC in order to comprehend the internal architecture and locate the three different domains: headwall, translational and toe (sensu Bull et al. 2009). However, when it comes to describe the chaotic mass, most authors tend to simply define it as chaotic seismic facies (e.g. Frey-Martinez et al. 2005; Gafeira et al. 2010; Fukuda et al. 2015; Berton and Vesely 2016; Omeru and Cartwright 2019). The present study is a first effort to separate different chaotic seismic facies as well as locate them within a deposit. This investigation used 2-D lines and 3-D surfaces in order to comprehend the spatial distribution of these different chaotic seismic facies and relate it with the topography at the time of deposition.

The investigation of chaotic seismic facies is becoming feasible since the quality and resolution of seismic surveys is increasing. This examination can provide better insights when looking at regional seals and/or reservoirs in deep-marine settings, since it provides suggestions regarding internal disintegration. In addition, when connecting with source area this investigation can become more reliable, since the original lithotypes are known.

The object of this study is the Maricá mass-transport complex (MMTC) which is in the southeastern margin of the Brazilian coast (Figure 1A), approximately 150km from Rio de Janeiro State. The MMTC covers an area of 1050km², is 35km long and 30km wide and has an average thickness of 150m, and an approximate volume of 150km^3 (Carlotto and Rodrigues 2009) (Figure 1B).

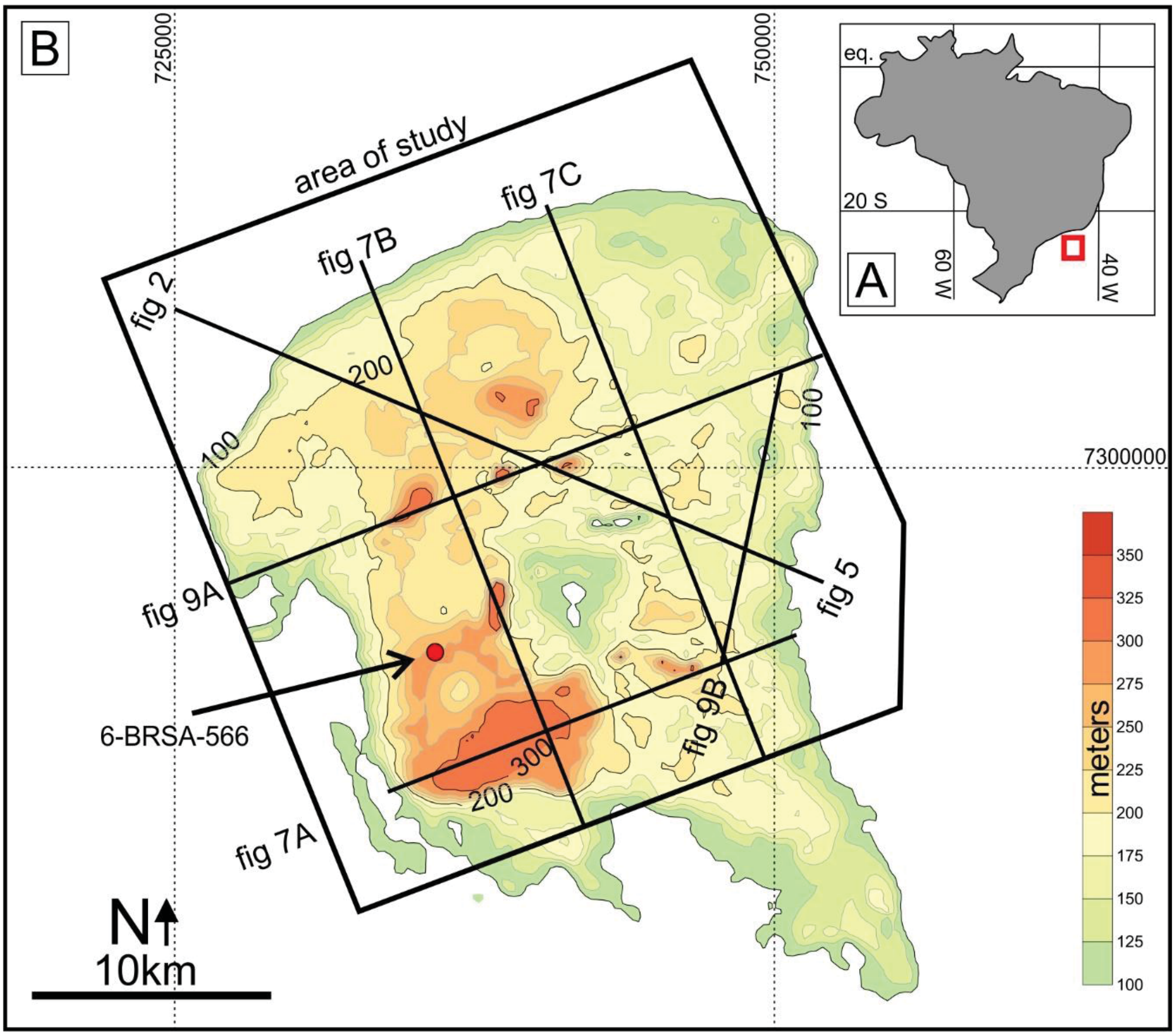


Figure 1. Area of study and the Maricá mass-transport complex (MMTC). A) Area of study in the red square approximately corresponds to the area of the figure B. B) Isopach map adapted from Carlotto and Rodrigues (2009) as well as the location of the 2-D lines showed in this paper.

2 Geological context

Representing almost 60% of daily Brazilian petroleum production (ANP 2019), the Santos Basin is in the southeast Brazilian continental margin (Figure 1A). The basin represents approximately 140Myr. of evolution, since the breakup of Gondwana and the opening of the South Atlantic Ocean until the present (Moulin et al. 2010). This evolution is represented by three super chrono-lithostratigraphic sequences (sensu Moreira et al. 2007). The rift supersequence comprises the early stages of the basin evolution. It contains basalts (Camboriú Fm.), heterolithic sandstones, conglomerates and siltstones (Piçarras Fm.), and carbonate rocks and shales (Itapema Fm.). The post-rift supersequence features variability between continental and shallow marine environments and it is composed of two formations: Barra Velha (microbialites) and Ariri (evaporites). Lastly the drift supersequence, the most complex sequence, displays halokinetic phases and tectonic events associated with the basin evolution (Caldas and Zalán 2009). The drift supersequence is comprised by Camburi, Frade and Itamambuca groups and represents environments that evolved from shallow marine water to deep marine water. (Supplementary material A).

3 Dataset

The present study is based on the analysis of a seismic public dataset provided by the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP). It is a Kirchhoff Post-Stack Time Migration (PSTM) that covers an area of approximately 1000km^2 (Fig. 1). The dominant frequency varies with depth and is 30Hz in the level of interest, resulting in a vertical resolution of approximately 30m ($\lambda/4$) assuming a velocity of 4000m.s^{-1} based on the well 6-BRSA-566.

4 Methods

The interpretation strategy was separated in two phases. The first looked at both upper and basal surfaces of the MMTC which will be referred to as external features. The second looks at the interior part of the MMTC and is here referred to as internal features.

The upper and basal surfaces of the MMTC (Figure 2) were manually picked using a snap-to-event feature. After mapping both surfaces in a 2x2 inline-crossline step they were then gridded using a triangulation algorithm with a nearest neighbor interpolation distance. Both surfaces then were filtered by the median in order to create a smoother surface and decrease the presence of artifacts created by poor gridding.

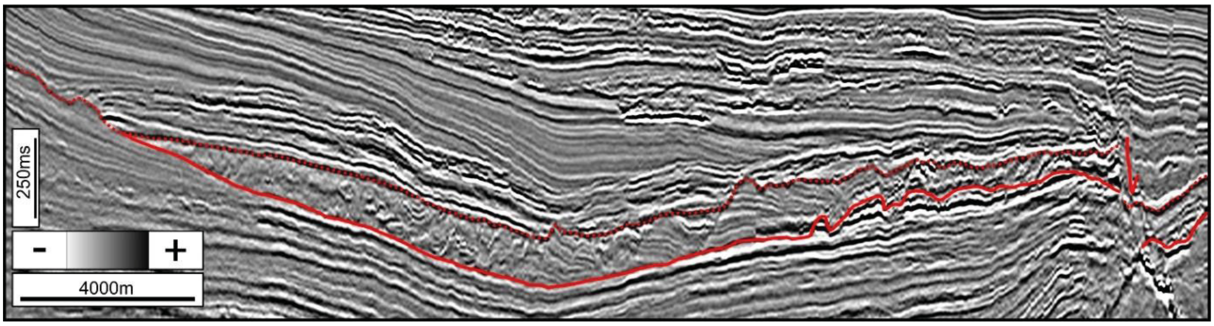


Figure 2. Seismic line showing both upper and lower surfaces of the MMTC. For section location, see figure 1.

Since a velocity model was not available for the entire seismic volume and the use of a single seismic-well velocity model would provide an erroneous model for the whole area we decided to digitalize the isopach map (Fig. 1B) from Carlotto and Rodrigues (2009) and re-grid it. This process was made using qGIS 3.2 where lines were created and then split into X, Y, Z point data. The data was filtered by deleting Z values lower than 100m, since the vertical resolution is not ideal for thin sections of the complex. The data was then gridded using a triangulation algorithm with a nearest neighbor interpolation distance on Surfer 8 by Golden Software. The resultant map allowed us to visualize lateral continuity and lack of deformation. Based on this information we could generate 2-D seismic lines in positions where it would transect most information as possible.

The upper surface (Figure 2) was used as a chronostratigraphic horizon datum generated by flattening this surface. This horizontalization correlates to the Maastrichtian period, when the MMTC was deposited (Carlotto and Rodrigues 2009). Since the area has halokinetic deformation (Caldas and Zalán 2009) this horizontalization probably created distortions and artefacts (Bland et al. 2004, however we decided to interpret the direct product of this horizon flattening.

A Shaded Relief attribute was used to highlight structural features (e.g. scars and faults). This attribute was calculated following the workflow proposed by De Groot and Bril (2005) and Farrukh (2009). This azimuthal illumination was set to 300, perpendicular to the flow main direction.

In order to access the internal features of the MMTC a 3-D surface was created by adding 50ms to the upper surface. This new surface gave us chance reach the internal characteristics via Dip-steered similarity. Added to this plan-view description, a cross section-view description was done via 2D lines located both perpendicular and parallel to the flow direction. This description was based on length, lateral and vertical continuity, as well as geometry of the chaotic reflections.

The Similarity attribute was generated using a Principal Component Analysis (PCA) dip-steering as a seismic event guide (Brouwer 2009) resulting in a more trustworthy product when comparing to a standard similarity attribute (De Groot et al. 2004). This Dip-steered Similarity attribute generation followed the workflow proposed by Brouwer (2009) and De Groot and Bril (2005). This attribute highlights different seismic facies and structural discontinuities and in the present research was used to visualize the presence and the extent of major remnant and relict blocks located in the MMTC.

In addition, this paper also uses the terms relict and remnant blocks. The term relict block refers to coherent blocks of sediments that were transported within the failed mass (Frey-Martinez et al. 2005; Bull et al. 2009). The term relict block also represents coherent blocks of sediments; however, it is clearly rooted to the strata right below it (Frey-Martinez et al. 2005). This also include relict blocks which visibly underwent short movement since it is possible to visualize this characteristic when looking at the basal surface. However, it is still possible to recognize the rooted strata.

5 Results

The results are divided into two groups. The first group corresponds to the non-flattened interpretation which is divided into external and internal features. The second group corresponds to the flattened interpretation and is also divided into external and internal features.

5.1 Non-flattened

5.1.1 External features

The isopach map (Fig. 1B) shows the thickness ranging mainly from 100 to 375m (see 4.1) and the dimension of the complex. It is also possible to notice the presence of two different zones. One zone is in the eastern region, which is majorly characterized by thinner values (<200m) and by having a long spread zone. The second, located in the western region, is characterized by thicker values (>200m), and by having a shorter spread zone.

Analyzing the structural time map (Fig. 3) it is possible to observe the extent of the upper surface of the MMTC (Fig. 2), as well as the presence of three major seismic topographic features in the area of study. The first is a salt-related dome located in the western portion. The second is the presence of a ramp-like structure located in the southern portion of the complex. The third feature is in the northern area and is characterized by an abrupt depth change, from 2900ms to 3250ms. In plane-view (Fig. 4) this area is identified by the presence of discontinuities and crown-cracks, which characterizes both flow direction and the existence of a headwall domain (Bull et al. 2009). It is also possible to roughly identify the transition from the headwall to the translational domain by the decrease presence of discontinuities (Fig. 4). However, when looking at the cross-section-view (Fig. 5) both headwall and translational domains become easily identified, as well as its transition. The headwall domain is characterized by an erosive scar that has possible younger on-lapping turbidites on top (Fig. 5A). The translational domain starts where the horizon that characterizes the erosive scar split into two horizons: upper and basal (Fig. 5A, B). The upper horizon is easily recognized throughout the entire complex and is defined by a strong positive contrast (Fig 5A, B, C). The basal horizon is distinguished when the chaotic facies stops and it is possible to recognize the parallelism of the underlying surfaces; also, it is possible to identify an infrequent weak positive contrast (Fig. 5B, C). The transition from the translational to the toe domain (Fig. 5C) is only noticeable when looking at the internal features, since there is no major external feature that highlights this passage. It is also possible to recognize that the remnant blocks underwent some movement though the basal surface (Fig. 5C).

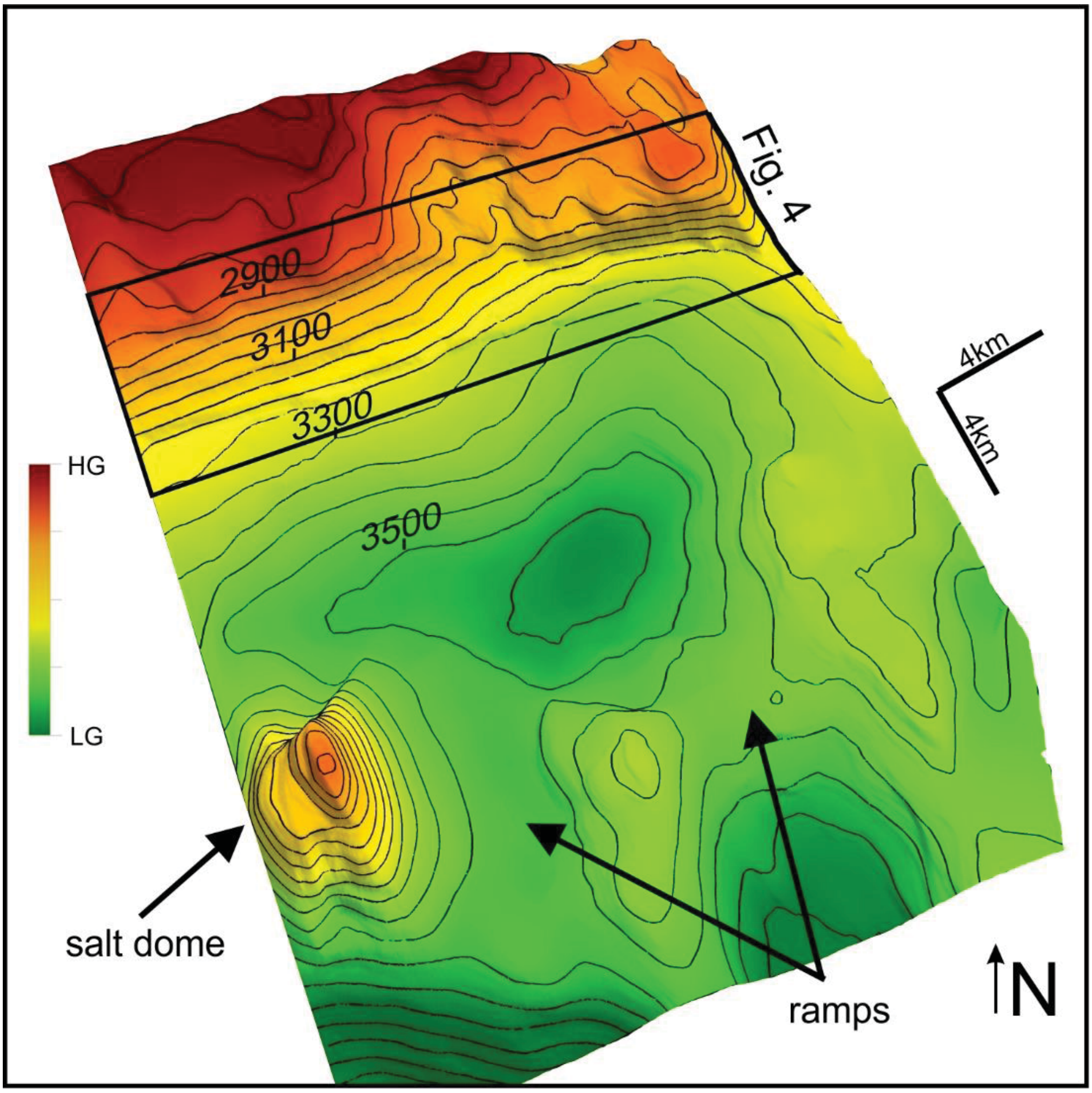


Figure 3. Structural time map of the upper surface of the MMTC showing the complexity of the area of study. In this area it is possible to identify three major topographic features: ramps, salt dome related structure and a major change in depth. HG: Higher ground; LG: Lower ground.

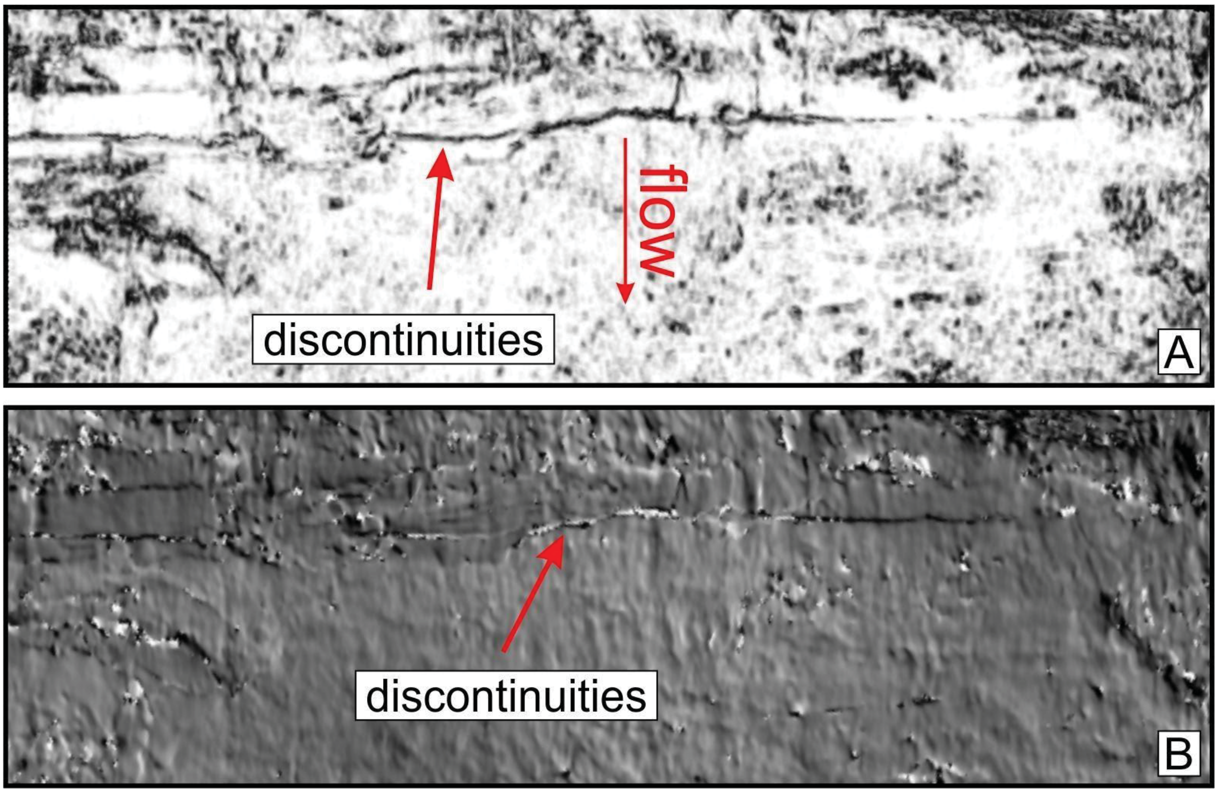


Figure 4. Plane-view of the headwall domain of the MMTC showing the presence of major discontinuities. A) Headwall domain with the use of the similarity attribute. B) Headwall domain with the use of the shaded-relief attribute.

5.1.2 Internal features

When looking at the non-flattened cross-view section (Fig. 5) it is possible to identify the presence of three different domains (sensu Bull et al. 2009). The headwall domain is characterized by an erosive scar (Fig. 4A), meaning that is not possible to access its internal features. The translation and the toe domain are characterized by the presence of different chaotic seismic facies, relict and remnant blocks (Fig 4C). These different chaotic seismic facies are better characterized after the flattening of the upper surface (5.2.2).

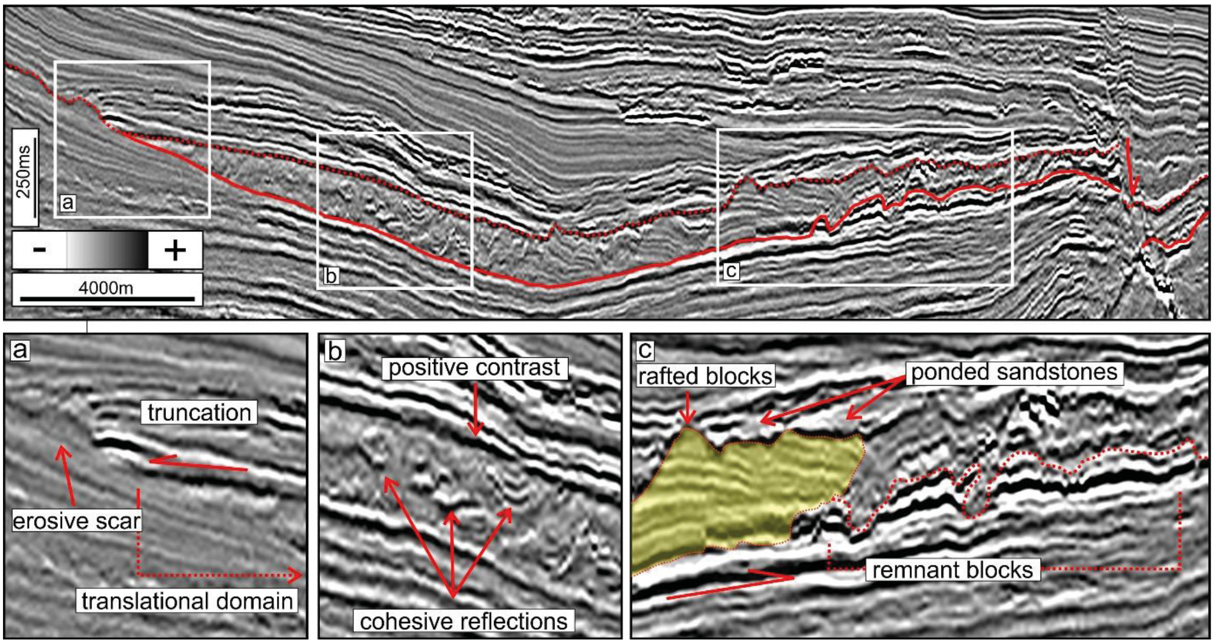


Figure 5. Cross-section of the MMTC showing the main domains as well as the presence of remnant and relict blocks. A) Transition from the headwall to the translational domain; it is possible to note the presence of an erosive scar as well as onlapping of possible turbidites on top of it. B) Translation domain with the presence of the strong positive contrast that is characteristic of the upper surface of the MMTC as well as the presence of cohesive reflections. C) Toe domain showing the remnant blocks and the presence of relict blocks as well remnant blocks. For section location, see figure 1.

5.2 Flattened

5.2.1 External features

Now using the upper surface as a datum and the basal surface as the underlying topography (Fig. 2) it is possible to characterize the basal topographic framework were the MMTC was likely deposited. In this heterogeneous topographic surface (Fig. 6) it is possible to identify the presence of two major channels: western and eastern (Fig. 6). Both channels have a NW-SE direction and are separated by a major remnant block (Fig. 6, Fig. 7A). The western channel is characterized by a smooth and deep topography where it is possible to observe lack of remnant blocks (Fig. 6; Fig. 7A, B), however, a 6km wide ramp-like remnant block is identified by the toe domain (Fig. 6, Fig. 7A, 7B). This structure is also observed at the non-flattened upper surface (Fig. 3) as well as the isopach map (Fig. 1B). The eastern channel is characterized by a rough, bumpy and shallow topography (Fig. 6, Fig 7A, 7C).

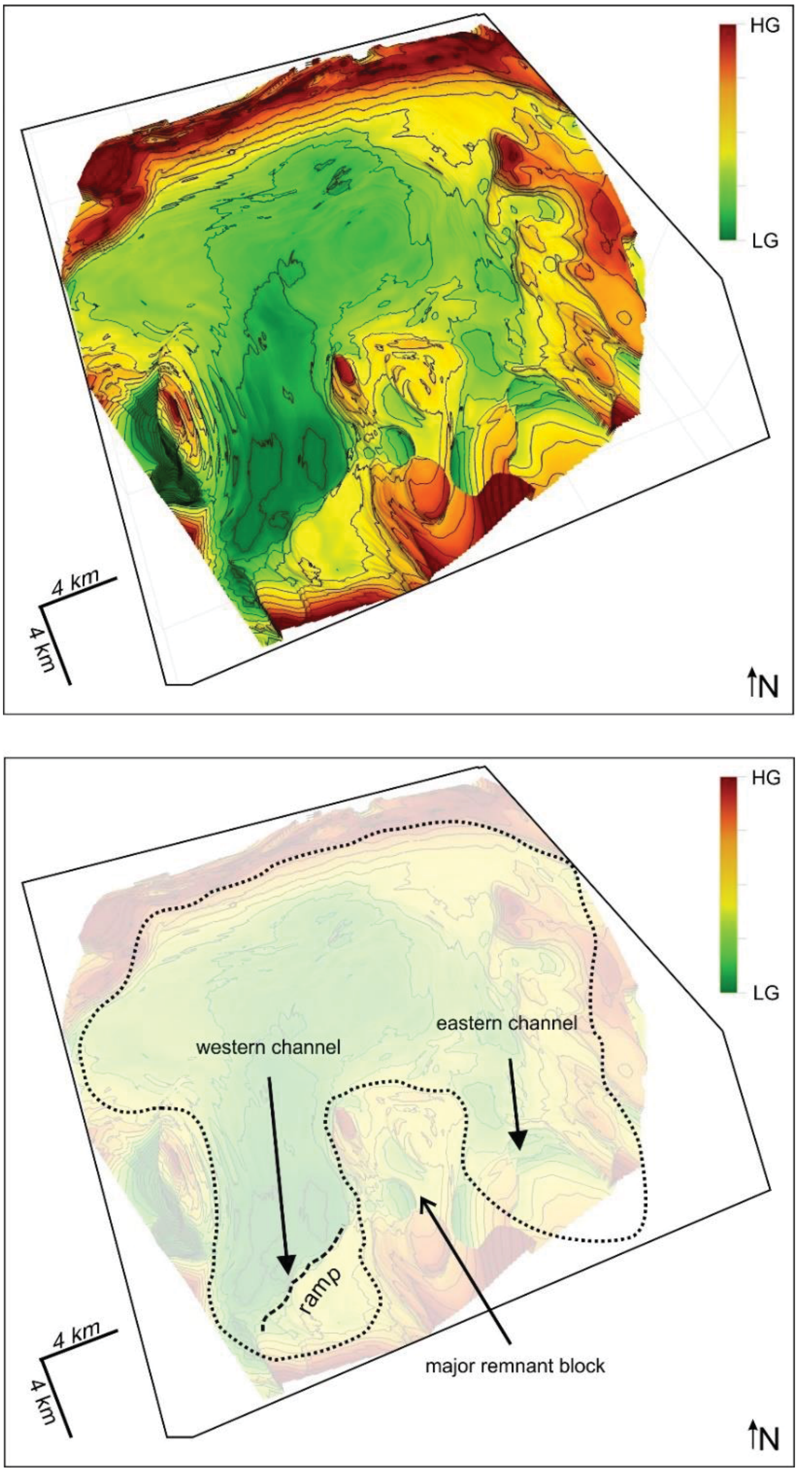


Figure 6. Basal topographic map using the upper surface as datum. HG = higher-ground; LG = lower-ground

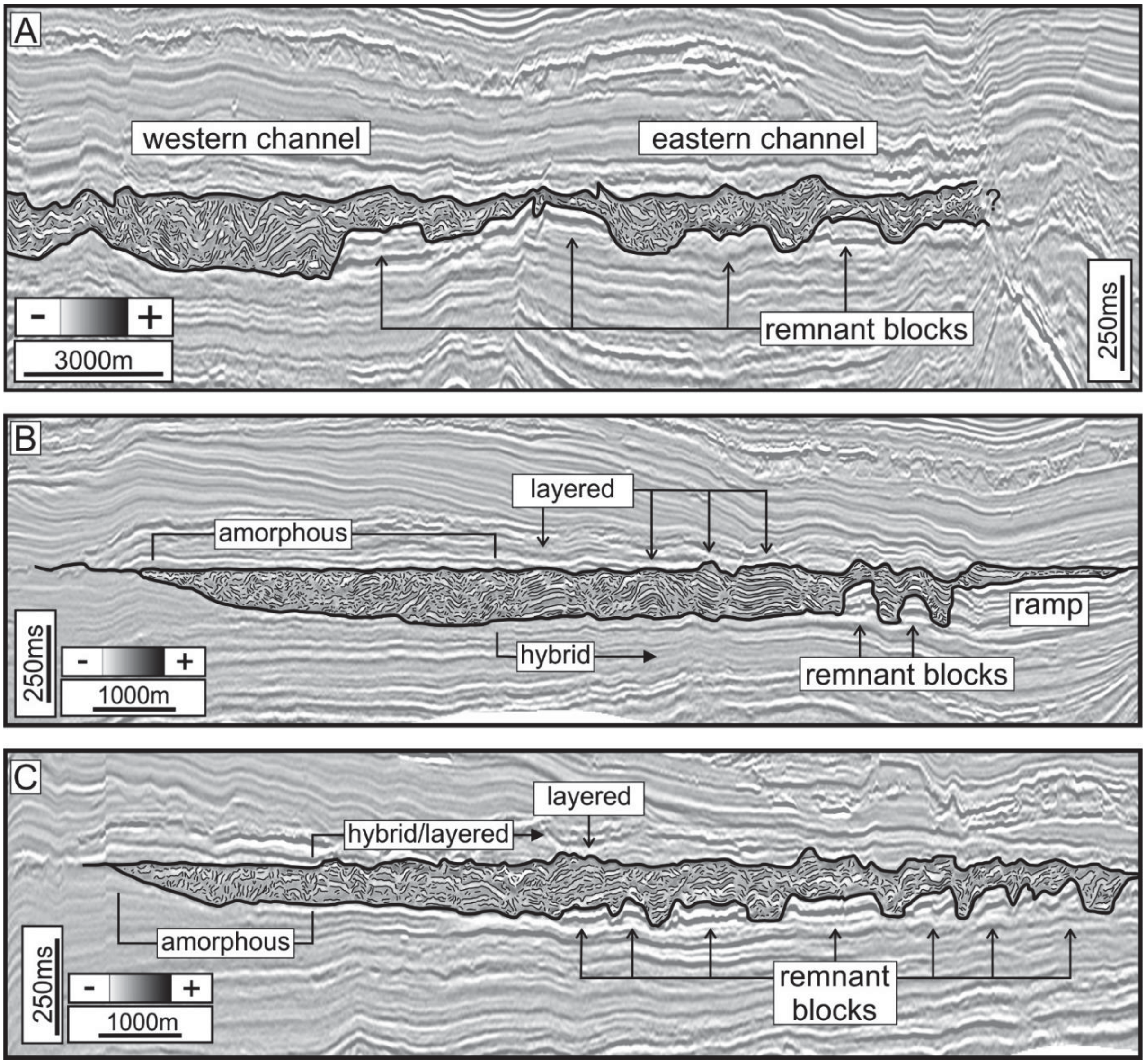


Figure 7. 2-D lines showing the presence of remnant blocks and the three different chaotic seismic facies. A) crossline showing the two different channels as well as the presence of major remnant blocks. B) in-line showing the profile of the western channel. C) in-line showing the profile of the eastern channel. For sections location, see figure 1.

5.2.2 Internal features

Internally the MMTC is characterized by three groups of chaotic seismic facies (Fig. 8). They are present in both in-line (Fig. 7B, 7C) and crossline (Fig. 7A; Fig. 9A). These different chaotic seismic facies can be described as amorphous, hybrid and layered (Fig. 8). The amorphous chaotic seismic facies is characterized by packages of coherent weak reflections that are involved in a transparent matrix. This facies is usually located in the transition between the headwall and translational domains and is characterized by reflectors with length varying from 100 to 300m. When looking at the eastern channel it is possible to note that this seismic facies is present for approximately 2km in the translation domain (Fig. 7C). However, in the western channel the same seismic facies it is present for at least 6km (Fig 7B). In plane-view (Fig. 10; Fig. 11) this seismic facies is identified by the darkest colors in the similarity map.

The hybrid chaotic seismic facies, when looking at the cross-view is characterized by imbricated and/or folded reflections with length varying from 200 up to 1000m. These chaotic facies are identified throughout the entire complex, however is more commonly described near relict and r blocks (Fig. 7B, 7C; Fig. 9A, 9B). In plane-view this chaotic facies is identified by dark-gray to gray colors (Fig 10; Fig. 11).

Lastly, the layered chaotic facies is described is cross-view as wavy, subparallel to parallel continuous reflections with length varying from 300 to 2000m (Fig 7; Fig. 9A). When looking at the plane-view map is possible to easily recognize this chaotic facies is identified by as bright white in the similarity map (Fig. 10; Fig. 11).

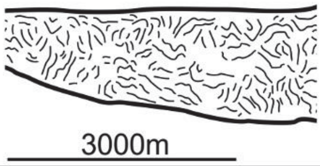
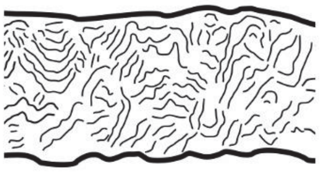
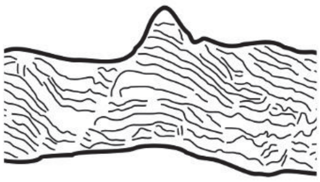
chaotic facies		cross-view description	plan-view description
	amorphous	Packages of coherent reflections within a transparent matrix. Reflections length varying from 100 to 300 meters.	Darkest colors at similarity. Usually located in the transition from the headwall to the translational domain.
	hybrid	Imbricated and/or folded reflections with length varying from 200 to 1000 meters. Sometimes is possible to identify rafted blocks within this chaotic facies.	Dark-gray to gray at similarity map. Usually located in the translational domain.
	layered	Wavy, subparallel to parallel continuous reflections with length varying from 300 to 2000 meters.	Light-gray to white at similarity map. Are interpreted as rafted blocks.

Figure 8. Chart synthesizing the different chaotic seismic facies.

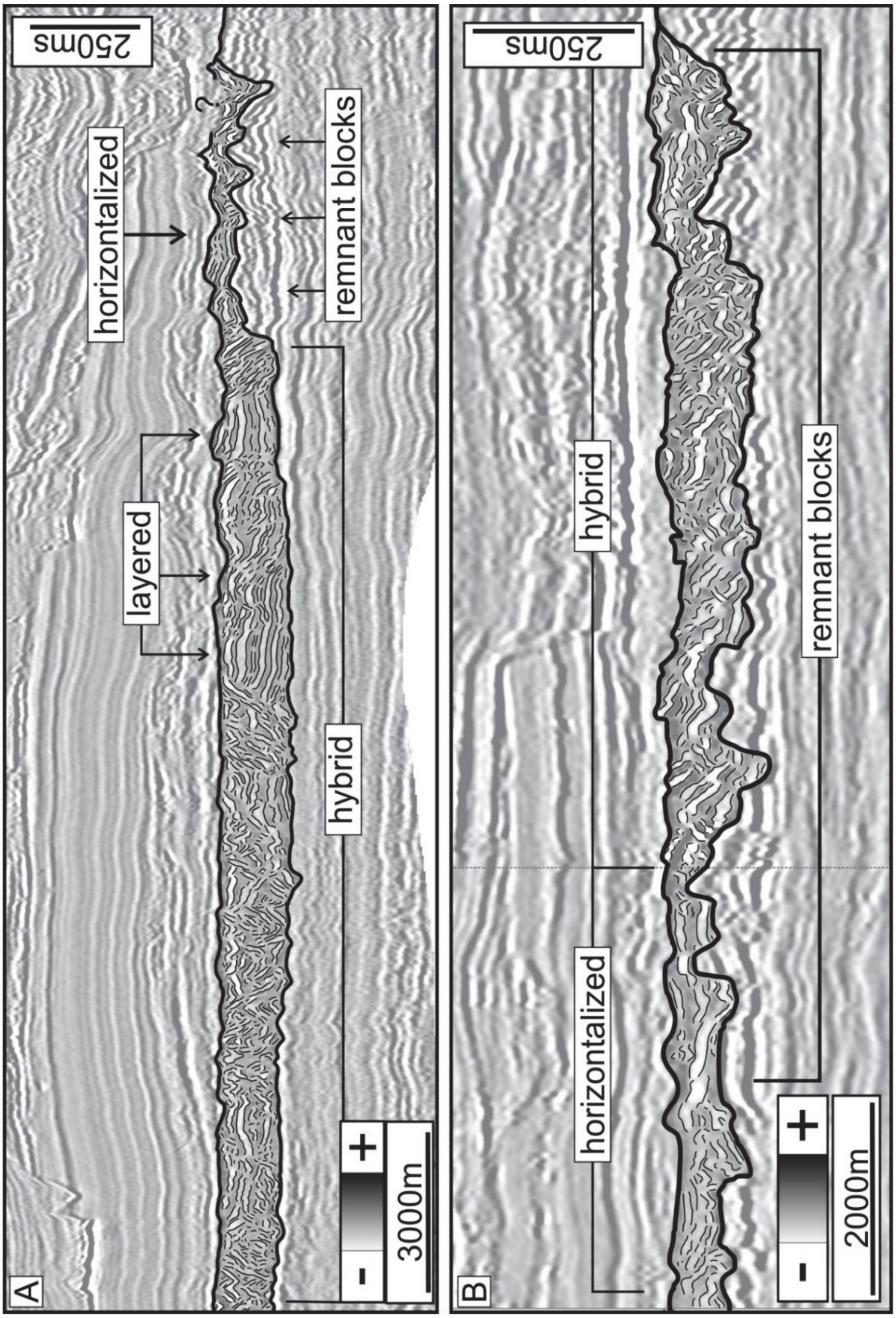


Figure 9. 2-D lines showing the different types of chaotic seismic facies present in the MMTC. A) crossline located in a position where the channeling is not present. B) Seismic line showing the horizontalization of internal reflectors when a remnant block is present. For sections location, see figure 1.

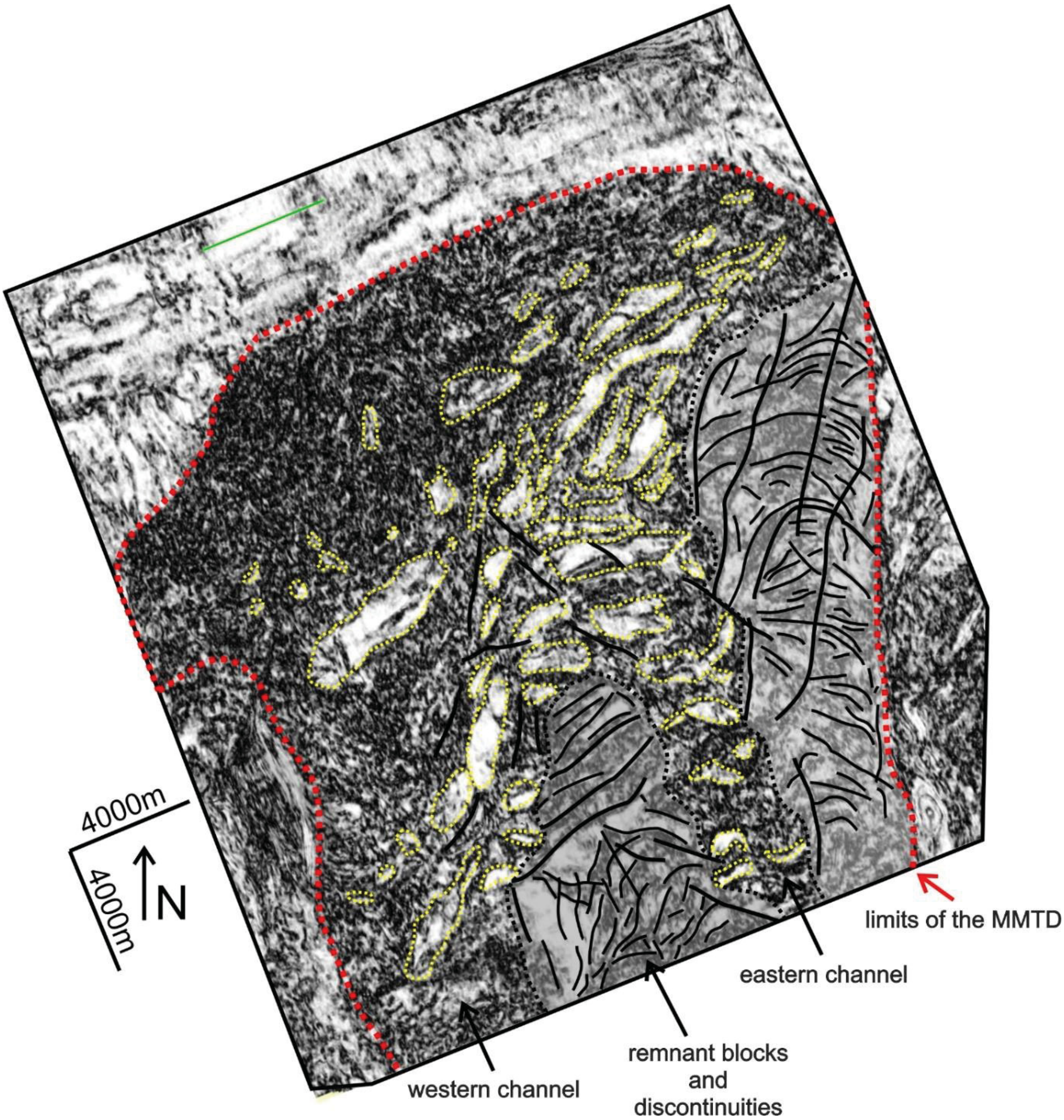


Figure 10. Internal features of the MMTC with the similarity attribute when adding 50ms to the upper surface the of the complex. The dashed-yellow lines are the interpretation regarding the limits of relict blocks. The dashed-black lines are the limits of remnant blocks, and the black lines are the discontinuities present in the MMTC.

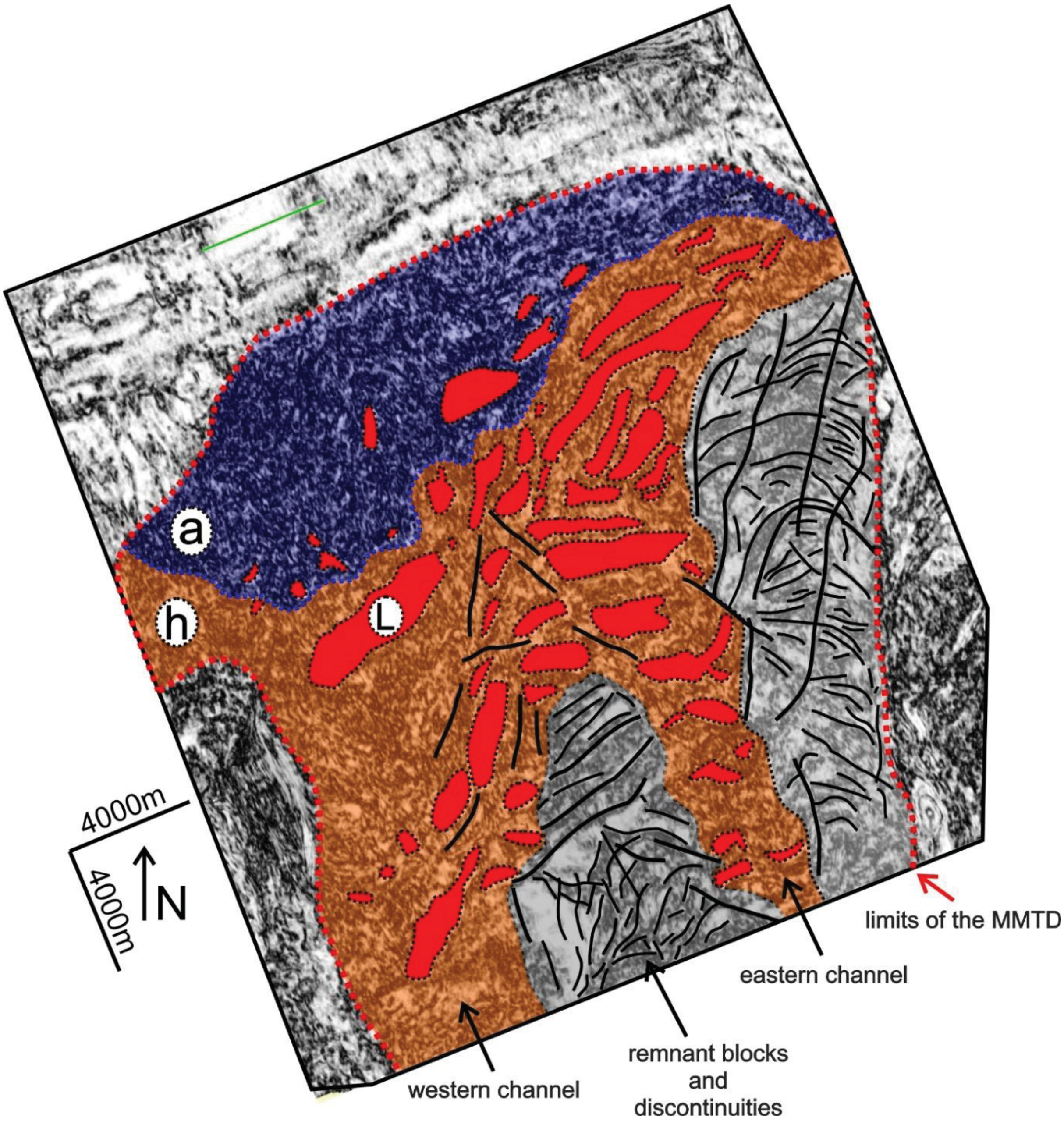


Figure 11. Spatialized internal features of the MMTC with the similarity attribute when adding 50ms to the upper surface the of the complex. The red blocks are the interpretation regarding the presence of relict blocks. The dashed-black lines are the limits of remnant blocks, and the black lines are the discontinuities present in the MMTC. A) Amorphous chaotic-seismic facies; H) Hybrid chaotic-seismic facies; L) Layered chaotic-seismic facies.

6 Discussion

The MMTC is a frontally-emergent (Frey-Martinez et al. 2006) and a slope-attached mass-transport event (Moscardelli and Wood 2008) that was the product of a single event, therefore is consider a complex.

6.1 Trigger and sense of movement

The MMTC is positioned in the middle of a major progradation period. This progradation is known as Juréia Progradation and was the result of major isostatic adjustments on the continental margin (Macedo 1989). These adjustments are related to the tectonic uplift of the Serra do Mar and Serra da Mantiqueira (Almeida and Carneiro 1998; Cobbold et al. 2001; Modica and Brush 2004), and were accompanied by the increase of sediment load and halokinetic movements (Zalán and Oliveira 2005; Assine et al. 2008; Caldas and Zalán 2009). It was in this context that the MMTC was likely triggered and deposited. The trigger itself is hard to determinate, however it is known that slope-attached deposits are associated with catastrophic events and extensive collapses in upper continental slope (Maslin et al. 2004; Maslin et al. 2005; Moscardelli and Wood 2008). Making feasible the possibility of the trigger to be related to earthquakes, marine currents, hydrate dissociation, long-shore currents, storms and/or hurricanes (Maslin et al. 2004; Maslin et al. 2005)

The sense of movement of the main flow was S30E. Differently from Carlotto and Rodrigues (2009), where the main flow was interpreted as S60W. We based our interpretation on the direction of the headwall scours (Fig. 4), as well as the presence of massive relict blocks oriented parallel to sub-parallel to the headwall scarp (Fig. 9). These blocks long-axis are elongated in the scarp direction and are associated with pre-existing extensional faults and the lack of disintegration (Frey-Martinez et al. 2005; Lastras et al. 2006).

6.2 Topography and the internal features of the different channels

The general topographic surface was the MMTC was likely deposited during the Maastrichtian is characterized by being rough (Fig. 4). However, when looking at the both different channels we can separate them into two types of surfaces. The western channel is flat and less bumpy than the eastern channel (Fig. 4.), and this flatness is also represented when looking at the internal chaotic seismic reflectors. When assessing the internal features from the western channel (Fig. 9), it is possible to note the smaller quantity of relict blocks within the range of the channel. A higher concentration of amorphous chaotic seismic facies is also noticeable in the beginning of the translational domain (Fig. 9). When looking at the eastern channel however, it is possible to note the higher quantity of relict blocks (Fig. 9) as well as a lower concentration of amorphous facies. This fact could be explained by the variability of strata disintegration due to different flow velocities (Nemec 1991; Gamboa et al. 2011; Posamentier and Martinsen 2011). The western channel is flatter than the eastern channel, and therefore has a higher velocity which produces more amorphous facies and internal disintegration. The eastern channel is bumpier and more irregular from the conception of the channel, likely causing the decrease of velocity and weaker disintegration during the movement. As a result of these topographic features, the first relic blocks in the Eastern Channel are noted in the first kilometers of the channel, while in the Western Channel the first relic blocks are not noted for 15 kilometers (Fig. 6B, 6C; 9). This interpretation is also reflected in the horizontal nature of the internal reflectors when looking in a cross-view. In areas with a lack of disintegration, due to reduced velocity as is prominent in the Eastern

Channel, results in horizontalized internal reflectors (Fig. 4C; 6A, B, C; 7A, B) (Bull et. al 2009; Gamboa et al. 2011).

In the case of the MMTC most of the disintegrated facies are in the more proximal areas while the less disintegrated facies are in the more distal areas (Fig. 11). This fact contradicts the normal tendency of mass-transport complexes and/or deposits to increase disaggregation through downslope flow transformation (e.g. Dott 1963, Fisher 1983, Nemec 1990, Martinsen 1994, Eyles and Eyles 2000, Dasgupta 2003, Fallgatter et al. 2016, Rodrigues et al 2020). The cause of this unique aspect is likely due to a sudden reduction of velocity when the flow departs the headwall domain to the translation domain and the flow starts to be affected by the presence of barriers. This explains why the amorphous facies is located in the proximal area and the hybrid/layered are located in the medial to distal regions. The horizontalization of reflectors in the presence of relict blocks (Fig. 9) corroborate this explanation.

6.3. Relevance for petroleum exploration

Analyzing the MMTC, where relict blocks and less deformed reflectors (layered and hybrid chaotic facies) are in the medial to distal regions of the complex and knowing that the source lithotypes are turbidites (Carlotto and Rodrigues 2009). Is feasible to expect that best reservoirs would be located far from the scarp, where the relict blocks controlled the lack of disaggregation. The best seals, however, would be located near the scarp, where the disaggregation is high. Another interesting aspect of the presence of relict blocks in the MMTC is that they control the deposition of the overlying rocks and create ponded sandstones deposits (Fig. 2; Fig. 5C).

7. Conclusions

- The Maricá Mass-transport Complex (MMTC) is a product of a Maastrichtian mass failure with a S30E direction;

- The internal access through the increase of 50ms on the upper surface showed to be a valuable way to examine the MMTC and investigate where relict blocks are;

- The flattening procedure was successful and enables us to visualize the topography where the complex was accumulated;

- The MMTC was heavily controlled by the topography and the flow flowed through two channels. Each channel shows different topography, and the internal characteristics reflected these differences;

- The bumpiness of the topography has a major role on controlling the velocity of the flow, this is reflected in the different chaotic seismic facies;

- Three chaotic seismic facies were characterized: amorphous, hybrid and layered;

- With increased prevalence of amorphous chaotic seismic facies the more significant disintegration is noted, the as consequence of the topographic features which cause a decrease in velocity.

Acknowledgements

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Supplementary material A

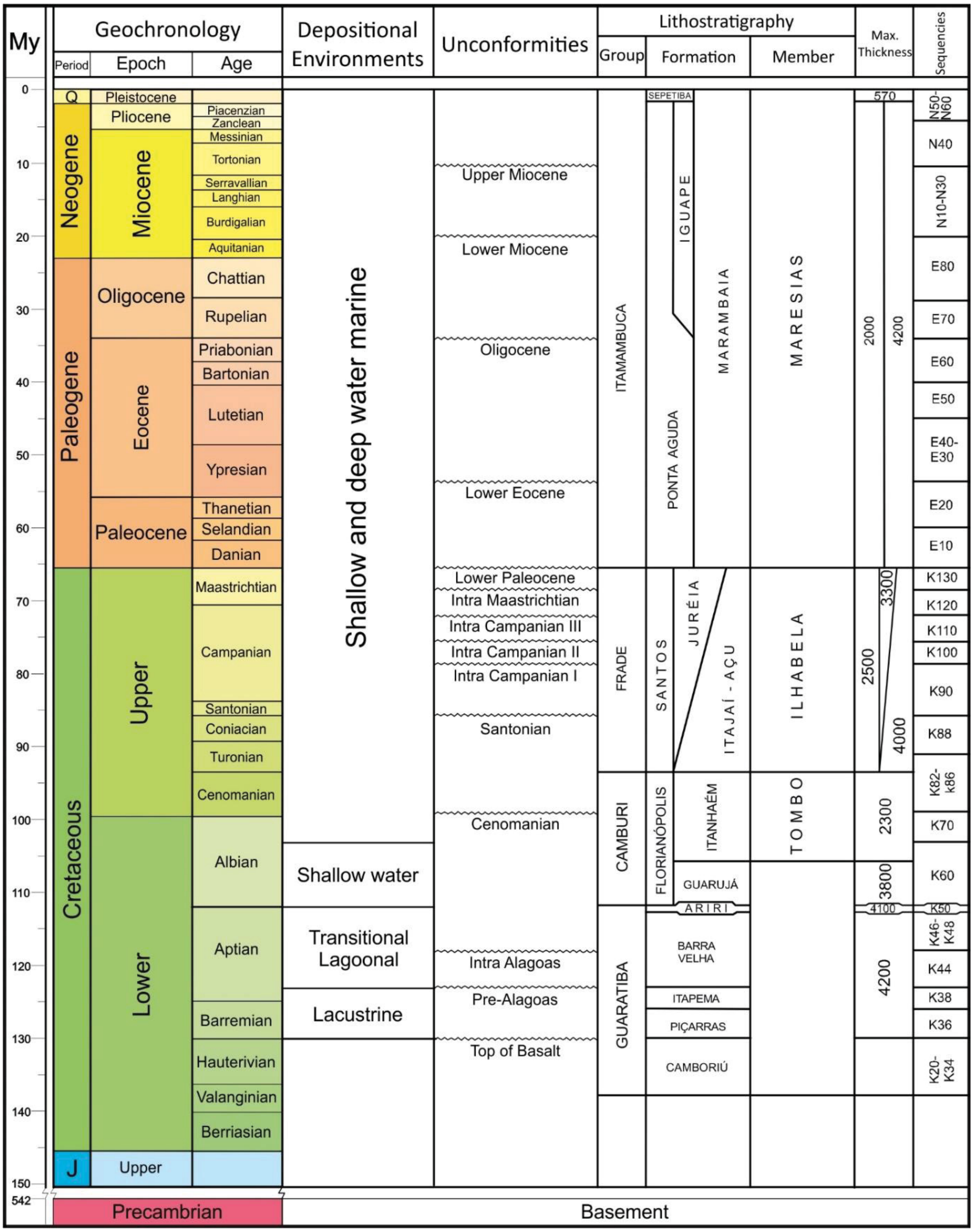

Figure 12. Santos Basin stratigraphic chart. This chart has been updated regarding color scheme, epoch and age according to Cohen et al. (2020). Modified from Moreira et al (2007)

3 CONSIDERAÇÕES FINAIS

- O estudo em detalhe do complexo de transporte em massa Maricá trouxe algumas reflexões referentes aos efeitos da morfologia num fluxo de transporte em massa;
- Constatou-se que a presença de grandes blocos remanescentes faz com que o fluxo seja desacelerado, resultando em diferentes sismofácies caóticas;
  - A sismofácies caótica amorfa é interpretada como uma total homogeneização dos sedimentos, e é a resposta de um fluxo rápido e sem obstáculos;
  - A sismofácies caótica híbrida é interpretada como homogeneização parcial de sedimentos, é usualmente encontrada perto de blocos remanescentes e/ou em jangada;
  - A sismofácies caótica acamadada é interpretada como a preservação do acamamento dos sedimentos, é a resposta da presença de blocos remanescentes e/ou em jangada;
- A distinção de três diferentes sismofácies caóticas pode trazer contribuições para a indústria do petróleo, já que a previsão de selos e/ou reservatórios poderá ser melhorada.

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